ELSEVIER

Available online at www.sciencedirect.com
ScienceDirect

Physics Procedia 5 (2010) 515–521

Physics Procedia

www.elsevier.com/locate/procedia

LANE 2010

On-line temperature monitoring in selective laser sintering/melting

*Yu. Chivel [a], I. Smurov [b]

[a] Institute of Applied Physical Problems, 7 Kurchatov Str. , Minsk , 220064 Belarus
[b] Ecole Nationale d'Ingénieurs de Saint-Etienne, 58 rue Jean Parot, Saint Etienne, 42100, France

Abstract

Poor efficiency of selective laser sintering/ melting (SLS/SLM) processes and poor articles surface quality are mainly responsible for their slow manufacturing application. That is why optical monitoring has paramount importance for SLS/SLM process resulting part quality.
The optical systems for temperature monitoring of SLS/SLM process are developed and integrated with industrial SLS/SLM machines. The system provides the possibility to spatial distribution of brightness temperature at two wavelengths and selected temperature profiles, calculation of colour temperature and express analysis of possible deviations of the maximum temperature from its optimal value. Optimal regimes of SLS process for the sintering of the high porosity powder body was determined.

Keywords: optical monitoring; selective laser sintering/melting; colour temperature; high resolution pyrometry

1. Introduction

In the SLS/ SLM process a scanned laser beam sinters or fully melts and solidifies the material locally in a powder bed accordingly to a 3D-CAD model which is cut into slices of defined thickness . Each slice gives a cross section area of the part. Layer by layer the 3D part is made.
Selective laser sintering / melting processes are extremely complex and multivariate and require a high level of monitoring and control. A major role can be played by the remote on-line optical process monitoring which allows any fluctuations from optimal condition to be observed. At present time, this line of the process monitoring is strongly developing [1-6]. In most papers the evolution of the optical emission from the melt in one or more spectral ranges was recorded and the process was monitored from the level or character of the optical signal. However for the precision control of the SLS/SLM processes the measurements of the main parameters of these processes – maximum surface temperature, temperature distribution in the processing area, size of the melt and control of their

* Corresponding author. Tel.: +37-5-17-217-46-24.
E-mail address: yuri-chivel@mail.ru.

1875-3892 © 2010 Published by Elsevier B.V. Open access under CC BY-NC-ND license.
doi:10.1016/j.phpro.2010.08.079

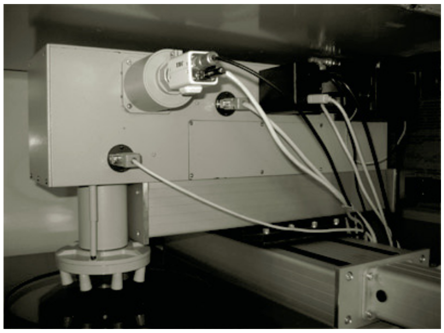
evolution are necessary. The surface temperature monitoring on the SLS/SLM processes by pyrometers and visualization by CCD camera presented in several papers [5-9]. In the present paper, development of on-line temperature monitoring systems with high temporal and spatial resolution adapted for SLS/SLM-process is discussed. The systems provide the possibility to measure spatial distribution of brightness temperature at two wavelengths and selected temperature profiles, calculation of colour temperature and maximum temperature in the focal spot**.**

2. Basics of temperature monitoring systems design

Temperature monitoring of the SLS/SLM process is based on optical measurements of temperature distribution at the sintering zone by videocamera and maximum surface temperature control in the irradiation spot using high speed two wavelengths pyrometer. The brightness and colour temperature measurements are based on Plank law , which describes the spectral density of electromagnetic radiation intensity emitted from a black body. On brightness or colour temperature determination the intensity of the thermal radiation from the surface in the region of laser action is recorded by CCD-camera or pyrometer in one or two spectral intervals and correlated with ones from the black body simulator, located in the same surface region. These temperatures are a conventional temperatures . The degree of its approximation to thermodynamic temperature is defined by the accuracy of the material emissivity determination.

In creation of temperature monitoring system, a combination of two types of optical sensors – 2D sensor – digital CCD camera and a single spot sensor- pyrometer based on photodiodes, which integrate thermal radiation emitted by a surface of certain size, are used. Both monitoring systems are developed and produced for the SLS machine (fig. 1 b) with a relatively large processing spot and a SLM machine (fig.1a) in which layers of powder material are fully melted in and around a very small laser spot, taking into account peculiarities of these processes.

a.



b.

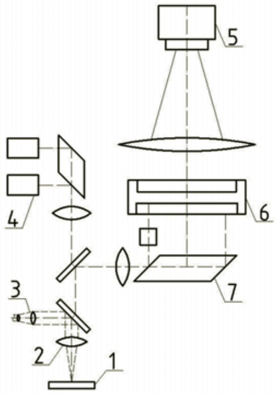
Fig.1. (a) Optical system for SLM process monitoring, integrated with SLM machine Phenix 100 ; (b) Optical system for SLS machine

The system of temperature monitoring for the SLS process is realized as a coaxial type system on a laser technological device with 2D plotter laser scanner setup. The camera with MCP plate and a pyrometer based on two diodes are adapted to the optic scanner through a 90^0 beam splitter, see Fig.2a. The scanner head was equipped with a 200 mm focusing lens which resulted in a focal diameter of 400 - 800µm.

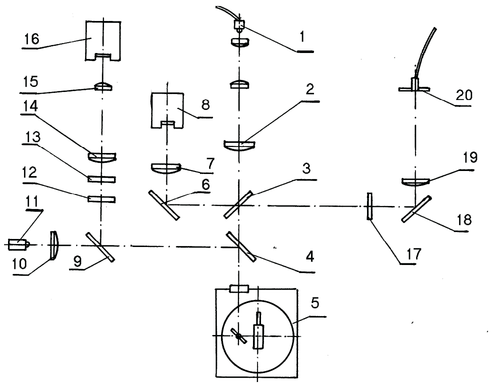
For SLM process monitoring the temperature monitoring system is equipped with a 2D laser galvo scanner setup. The CCD camera and a two channel pyrometer are integrated with the optical system of industrial laser machines Phenix 100 (Fig. 2b) through the system of gradient and dichroic mirrors [7]. The laser scanner ScanLab 14 was equipped with a 400 mm focusing lens which provides a focal diameter of 100 µm.

The systems are developed for monitoring of temperature distribution in laser irradiation zone based on registration using both a high speed digital CCD - camera or an intensified digital CCD- camera. The temperature distribution in a laser affected zone is observed with two different methods. Using the first method, the image of the sintering zone with five times magnification is projected onto the photocathode plane of a gated microchannel plate (MCP), see fig.2a.

Wavelength bands of λ_1 = 0.7 µm and λ_2 = 0.9 µm are spatially separated when radiation passes through a prism and thus two images are obtained (Fig. 3). The left image is recorded at λ_2 = 0.9 µm, and the right one (with low intensity) is recorded at λ_1 = 0.7 µm. The intensity profiles along the selected straight lines (horizontal and vertical ones) can be measured, and colour temperature is calculated, and distribution in the sintering zone is displayed (Fig. 3).

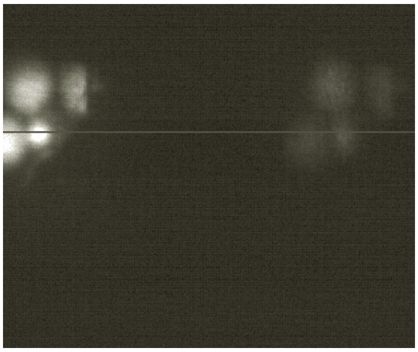


a.



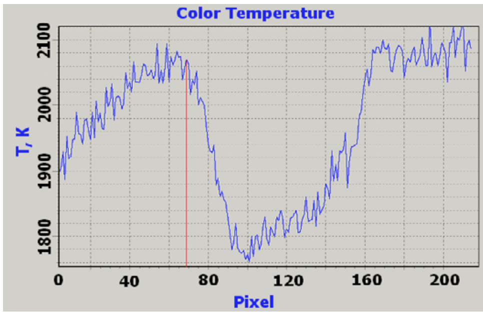
b.

Fig. 2. (a) Optical scheme of the system for temperature monitoring of the SLS machine: 1- working area, 2- focusing objective, 3- laser telescope, 4 - photodiodes, 5 – digital video camera, 6- MCP, 7 - prism with dichroic coatings ;
(b) Monitoring system for the melting process: 1- fiber laser output, 2 – telescope, 3,4 - gradient dichroic beam splitters, 5 - scanner head, 6,9,18 - dichroic beam splitters, 7, 10, 14,15,19 - lenses, 12,13,17 - filters, 8,16 - CCD – camera, 11 – LED, 20 - pyrometer fiber



200 µm

a.

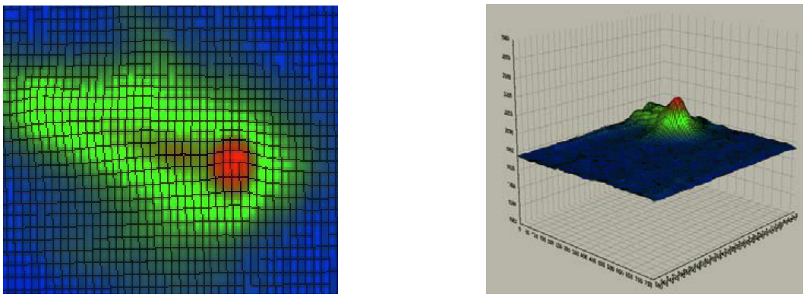


200 µm

b.

Fig. 3. (a) Spatial distribution of thermal radiation intensity at two wavelengths (the left image is recorded at λ_2 = 0.9 µm and the right image is recorded at λ_1 = 0.7 µm). Laser spot size - 600 µm. Spherical Ti powder ; (b) Spatial profile of recalculated colour temperature at the irradiation spot (along the line fig.3a)

In temperature monitoring system of SLM machine (fig. 2b) the image of the melting zone with magnification is projected onto the matrix plane of a digital CCD camera 16, and spatial brightness temperature distribution is determined (fig. 4).



____ 100µm

a. b.

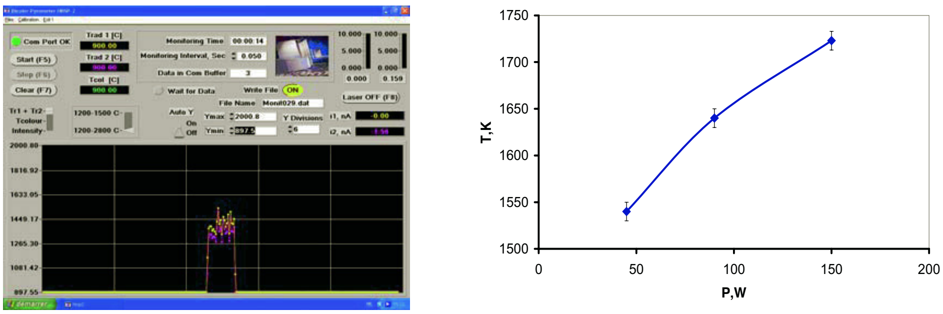
Fig. 4. (a) Spatial distribution of thermal radiation intensity at the irradiation spot in selective laser melting. Laser spot size -100 µm; (b) Spatial profile of recalculated brightness temperature at the irradiation spot

3. Peculiarities in SLM process temperature monitoring

As it is well known, mainly galvo scanner systems are used in modern SLM machines. The most frequently used interference scanner mirrors have selective character of reflection depending on the wavelength and the angle of rotation that must be taken into account in deciding on a spectral range of temperature measurements. Moreover, custom made F- teta lenses usually are not achromatic. This causes image shift in coaxial set-up sensor positioning systems and errors in measurements. 2 D sensors are tolerant to such shifts and this is their major advantage over single spot sensors.

But for continuous control of the melting process, measurement of the maximum surface temperature in the heat affected zone is preferable and most of all for manufacturing facilities. The principle of measurements was devised and a special optical scheme was designed to minimize image shift. Measurements are carried out at wavelengths close to the laser wavelength, which is prominent, using gradient type dichroic mirrors and filters.

A two-wavelength pyrometer based on two photodiodes registers the surface thermal radiation in the range of 900-1700 nm with time resolution 50µs and spatial resolution 50 µm. The image of scanning area is rendered on the fibre diaphragm, diameter of which demonstrates the area of signal integration. The photodiodes signals are amplified ($k = 10^6$) and gated with variable frequency and gate duration. Maximum brightness temperature in the sintering zone on two wavelenghts are displayed on fig. 5a. Simultaneous monitoring of the melting process with a video camera by means of recording the temperature distribution on the surface, and pyrometer enables to correlate the detected 1D-signal with real geometry of the melt. Fluctuations in temperature with 100 K in amplitude are due to nonuniform motion of the laser spot when scanning.



a. b.

Fig. 5. (a) Pyrometer output on the PC screen under laser melting of 50 µm Inox powder layer. Spot size – 100 µm, spot speed 100 mm/s, laser power 90W ; (b) Power dependence of surface temperature. Powder- Inox 316, scan speed -100 mm/s, layer thickness - 50 µm.- (b)

All temperature sensors calibration is performed by using a ribbon W- lamp or a W- halogen lamp with a transmitting diffuser, which is housed in the focal plane of the focusing objective 2 (fig.5). All lamps were previously calibrated with a black body model.

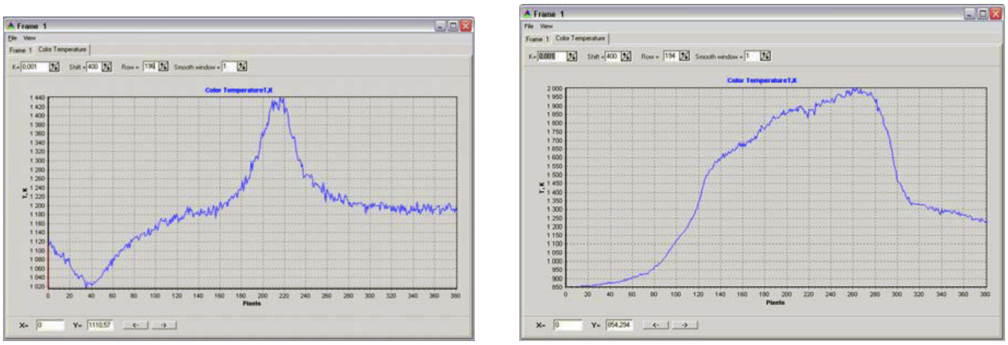
4. Temperature monitoring of the powder body sintering

Temperature monitoring makes it possible to optimize SLS of the powder body with a high range of porosity through connection of particles by liquid necks under Ti -particles surface melting during the pulse –periodic laser operation. It is difficult to realize SLS in the case of single – component metallic powder and create high porosity part through some negative effects one of which is "balling" effect [10]. Adjustment of SLS parameters must be strict . to prevent complete melting of particles and melt only thick surface layer of the particles.

A spherical Ti- powder with a diameter of 200 – 400 μm has been used. Changing the average laser power is carried out by changing the duration and amplitude of laser pulses at constant pulse frequencies – 4 Hz.

The diameter of the irradiation spot is maintained constant and equals 0.6-0.8 mm, which provides cover of several particles. Deposited powder layer ranges in thickness from 1 to 2 diameter of powder. As previously shown [11] the laser radiation is mainly absorbed by two layers of spherical particles .

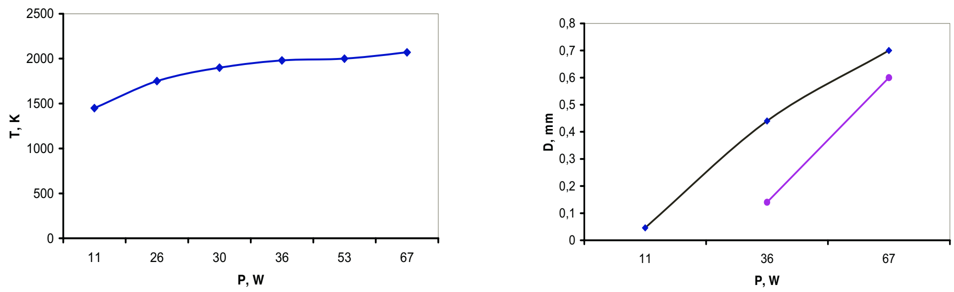
Sintering is conducted in a narrow range of scan speed – 0.4-0.8 mm /s. Under 2-3ms laser pulse duration and at the average power of 36-50W at these speeds a reliable contact sintering of Ti- powders occurred.



a. 200 μm b.

Fig. 6. Colour temperature distributiom in sintering zone at different average power: (a)- 11 W, (b) -36 W

The colour temperature in this case is within the 1900 K – 2070 K range. Influence of the average power on the spatial distribution of the surface temperature in the sintering zone has been revealed.

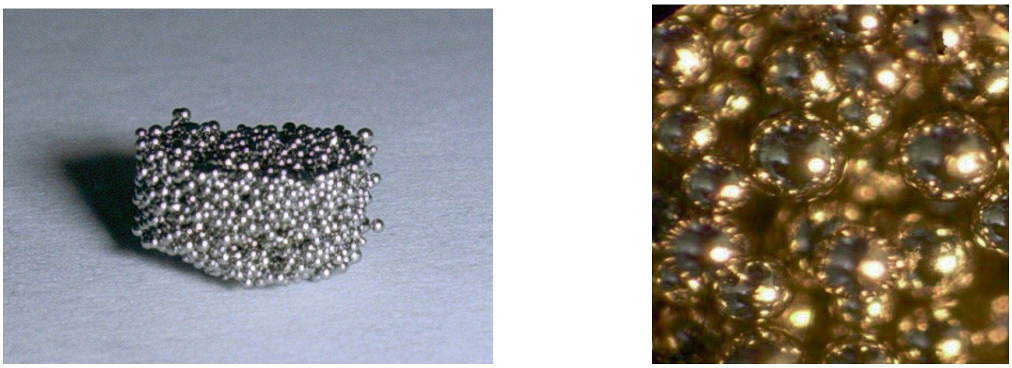


a. b.

Fig. 7. (a) - Average power dependence on the surface temperature ; (b) - Size of sintering zone versus average power (●) – level 1900 K , (♦) – level 1450 K . Pulse duration – 3 ms, frequency – 4 Hz, scan speed- 0.4 mm/s

It was determined that in the melt regimes the surface temperature has only weak dependence on the laser average power (Fig. 7a). Experimentally, it transpires that heat conductivity in the contact point between particles increases during surface melting and formation of the contact neck. This is evident from increasing of heat penetration area diameter (Fig. 7b).

As the results of experiments was found that the pulse- periodic regime of laser action with pulse duration and frequency allowed melting of thin ~ 50 – 100 μm layer of particles at a controlled temperature near the melting point of the particles material is optimum alternative for the production of high porosity powder part. Pilot specimens of such powder body have been fabricated, see Fig. 8.



300μm

Fig. 8. Multilayered powder body sintering from 300 μm spherical Ti- powder

5. Conclusion

On-line optical temperature monitoring systems adapted for industrial SLS/SLM-process are developed and applied for custom SLS/SLM machines. Process monitoring is based on optical measurements of temperature distribution in the sintering zone by a video camera and maximum surface temperature control in the irradiation spot using a high speed two wavelengths pyrometer. The on-line temperature monitoring makes it possible to optimize SLS of the powder body with a high range of porosity.

References

1. I.Smurov, M. Ignatiev, G. Flamant , J. of Measur. Sci. and Techn., 5 (1994) 563.
2. I.Decker, A. Heyn, D.Martinen, H. Wohlfahrt, Proc. of SPIE 3097 (1997) 29.
3. M.Muller , F.Dausinger, H.Hugel , Proc. ICALEO (1998) 85.
4. J.-P.Kruth, J. Duffon, P. Mercelis, et.al., Proc. of the LANE (2007) 23.
5. I. Smurov, Proc. IV Intern. Conf. on Lasers in Manufactoring, (2007) 537.
6. Yu.Chivel, I. Smurov, Proc.of IV Int. Conf. on Lasers in Manufacturing , (2007) 553.
7. Yu.Chivel, I. Smurov, B. Laget , Device for monitoring of the laser technological processes. Patent № 2371704 (2009).
8. Yu. Chivel, M. Doubenskaya, D. Zatiagin, Proc. V Intern. Conf. on Lasers in Manufacturing, (2009) 319.
9. Yu.Chivel, I.Smurov, D. Zatiagin, Izvestia Vuzov. Devices, 51 (2008) 70.
10. R. Morgan, C. Sutcliffe, W. O'Neil, Rapid Prototyping J. , 7 (2001) 159.
11. M. Petrushina, E. Pogudo , Yu.Chivel, High Temperature , 44 (2006) 148.